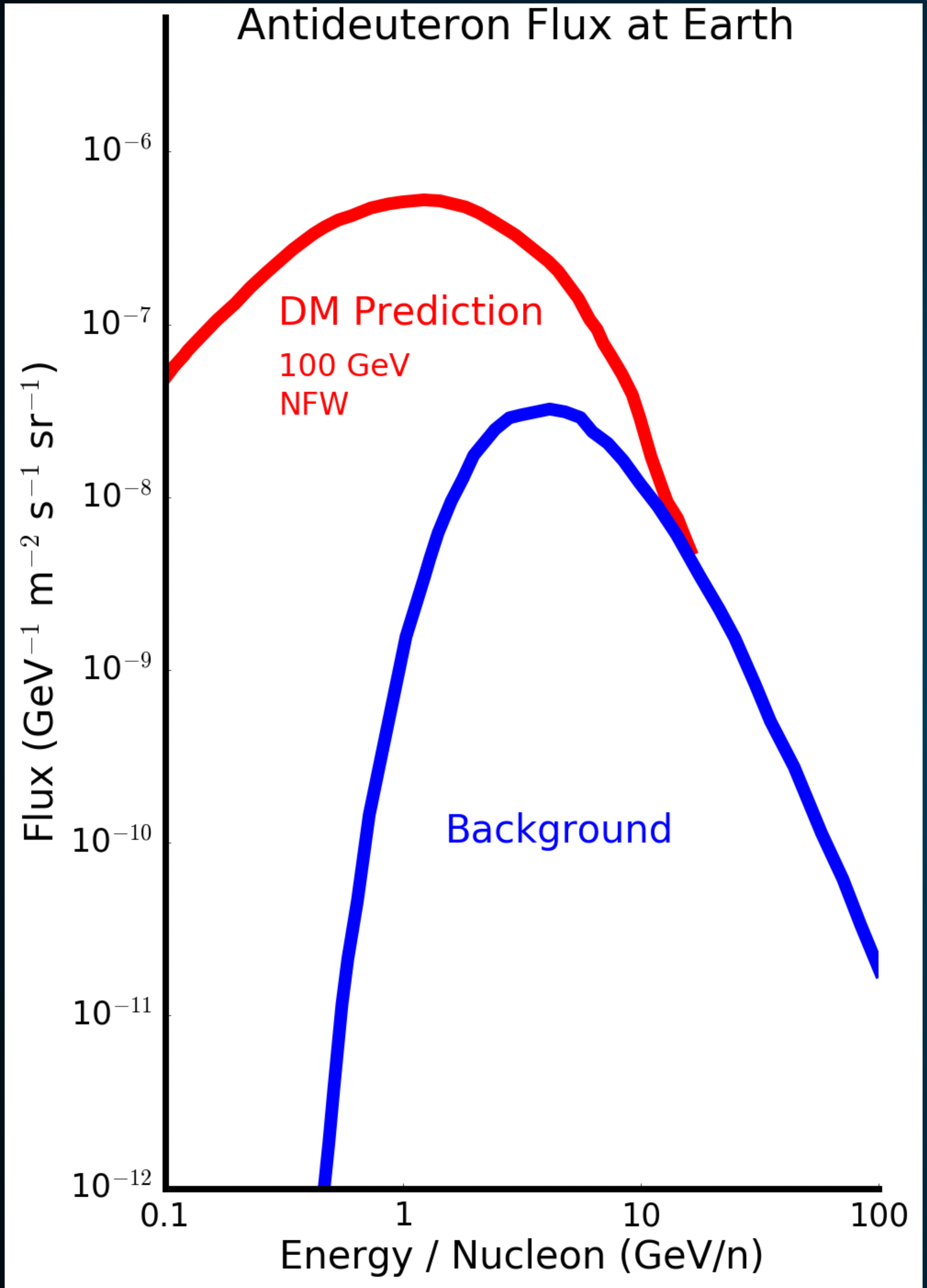
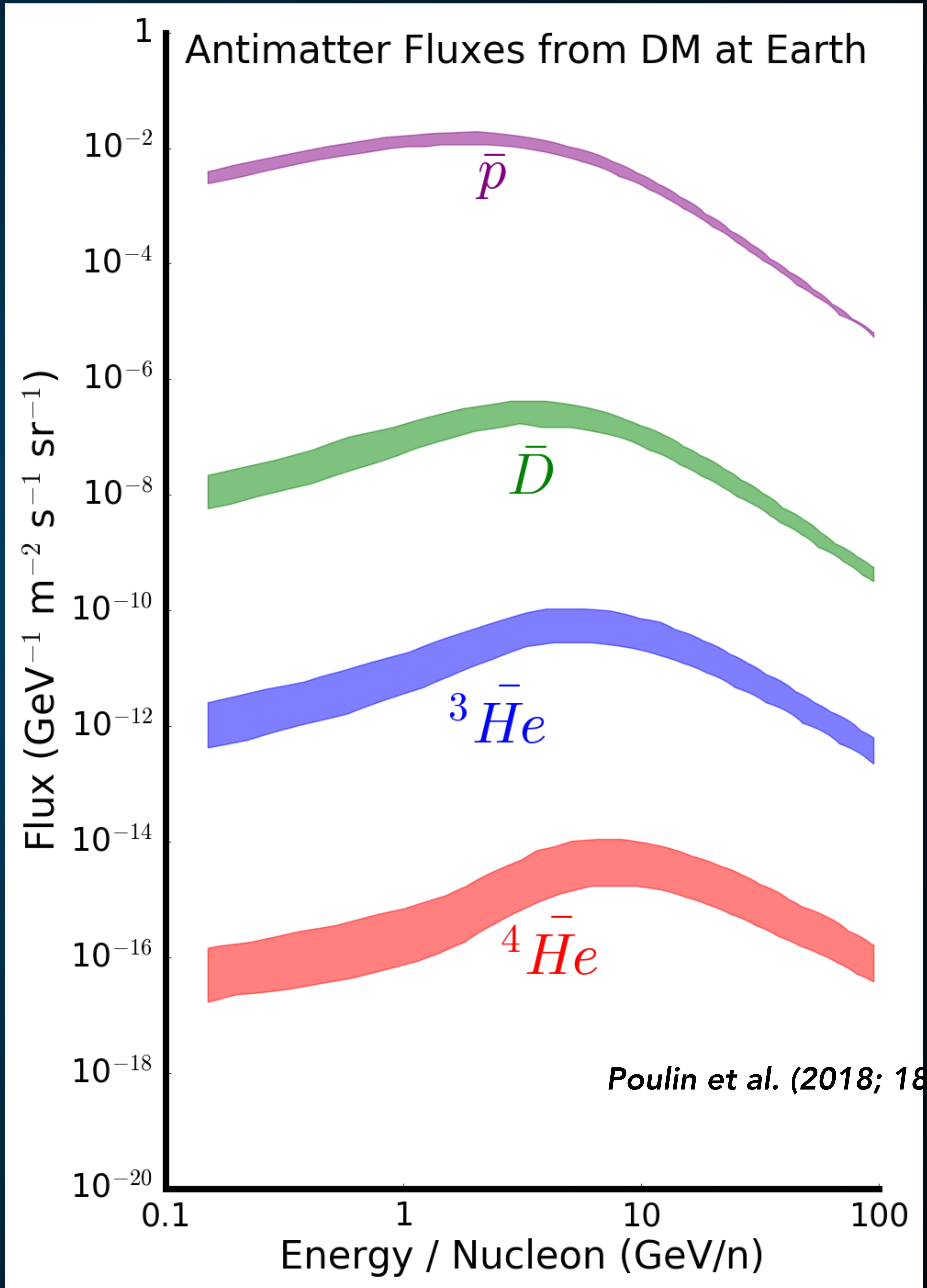
Tim Linden

Antihelium from Dark Matter Annihilation

Stockholms universitet

AntiNuclei: A Clean Search Strategy

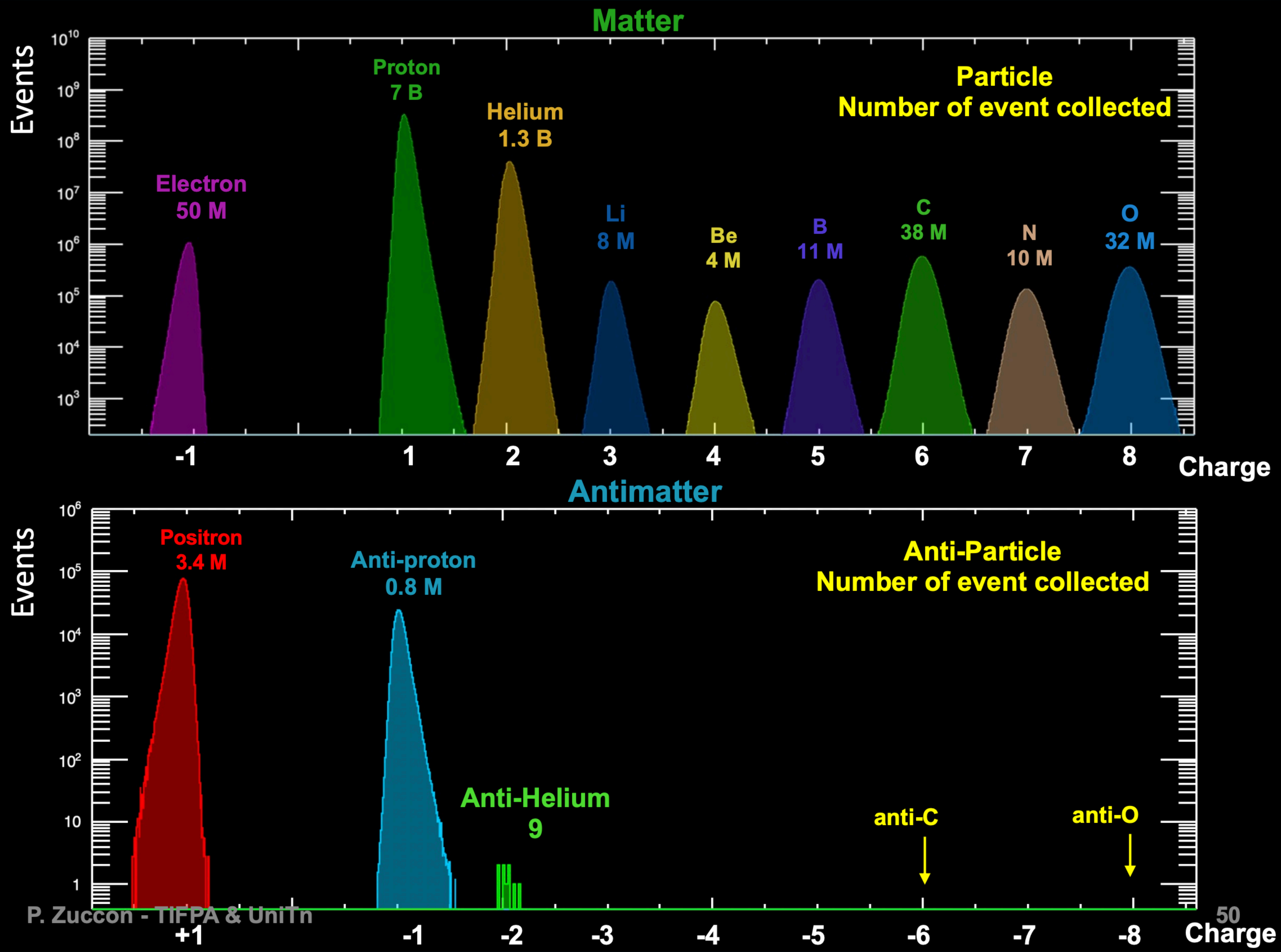




Poulin et al. (2018; 1808.08961)


NOT MY DEPARTMENT
BRILLIANT!
NOT MY PROBLEM

Tentative Evidence for Antinuclei


Matter
Events
Proton
7 B
Helium
1.3 B
Electron
50 M
Li
8 M
Be
4 M
B
11 M
C
38 M
N
10 M
O
32 M
Particle
Number of event collected
-1
1
2
3
4
5
6
7
8
Charge
Antimatter
Events
Positron
3.4 M
Anti-proton
0.8 M
Anti-Helium
9
anti-C
anti-O
Anti-Particle
Number of event collected
+1
-1
-2
-3
-4
-5
-6
-7
-8
Charge

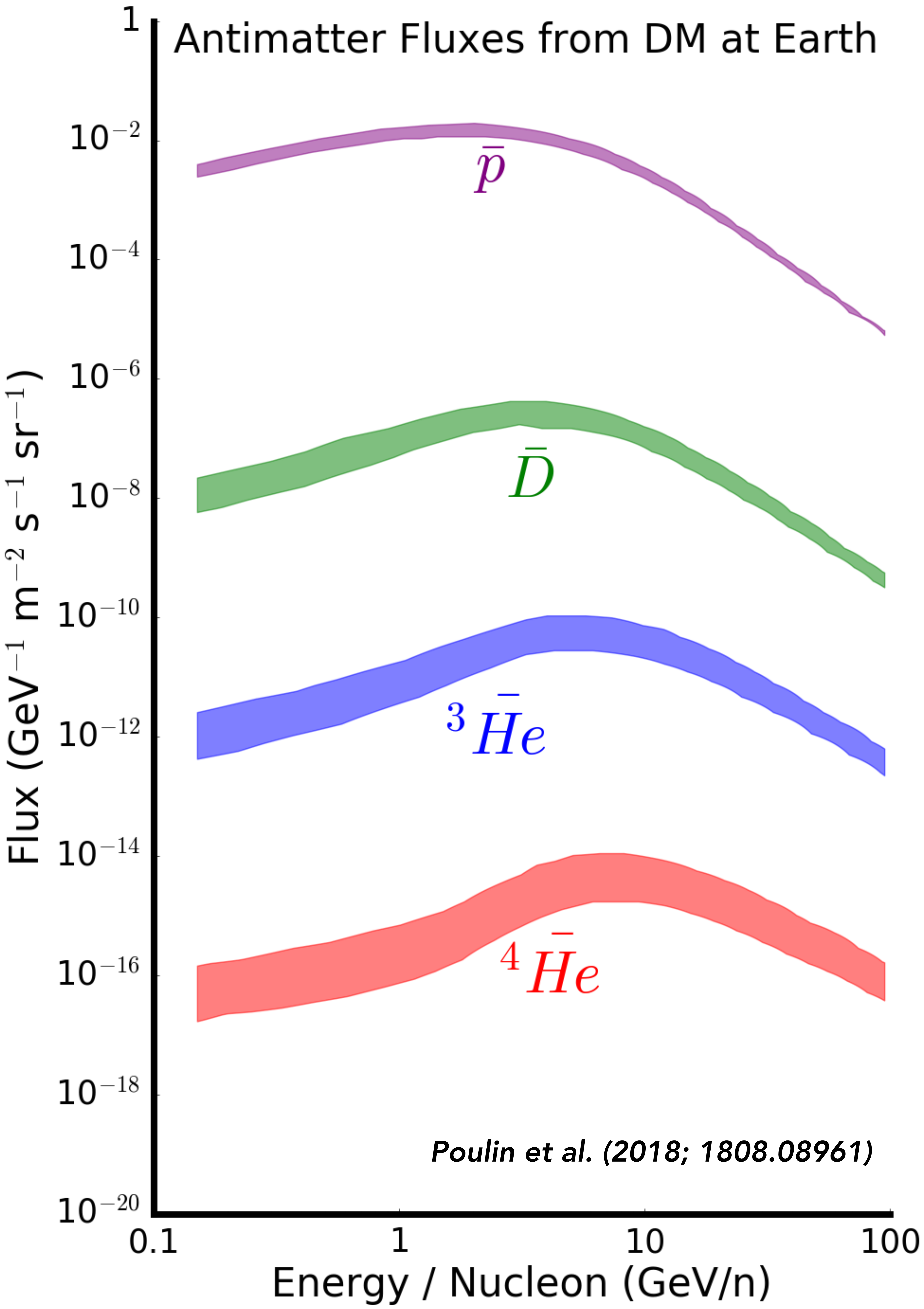
Chasing an AntiHelium Signal

1.) Coalescence Rates (1401.2461)

- Astrophysical Acceleration (2001.08749)

2.) Lambda_b Enhancement (2006.16251, 2106.00053)

3.) Strongly Coupled Dark Sectors (2211.00025)



$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{\bar{\mathrm{p}}} \frac{d^3 N_{\bar{\mathrm{p}}}}{dp_{\bar{\mathrm{p}}}^3} \right)^Z \left(E_{\bar{\mathrm{n}}} \frac{d^3 N_{\bar{\mathrm{n}}}}{dp_{\bar{\mathrm{n}}}^3} \right)^{A-Z}$$

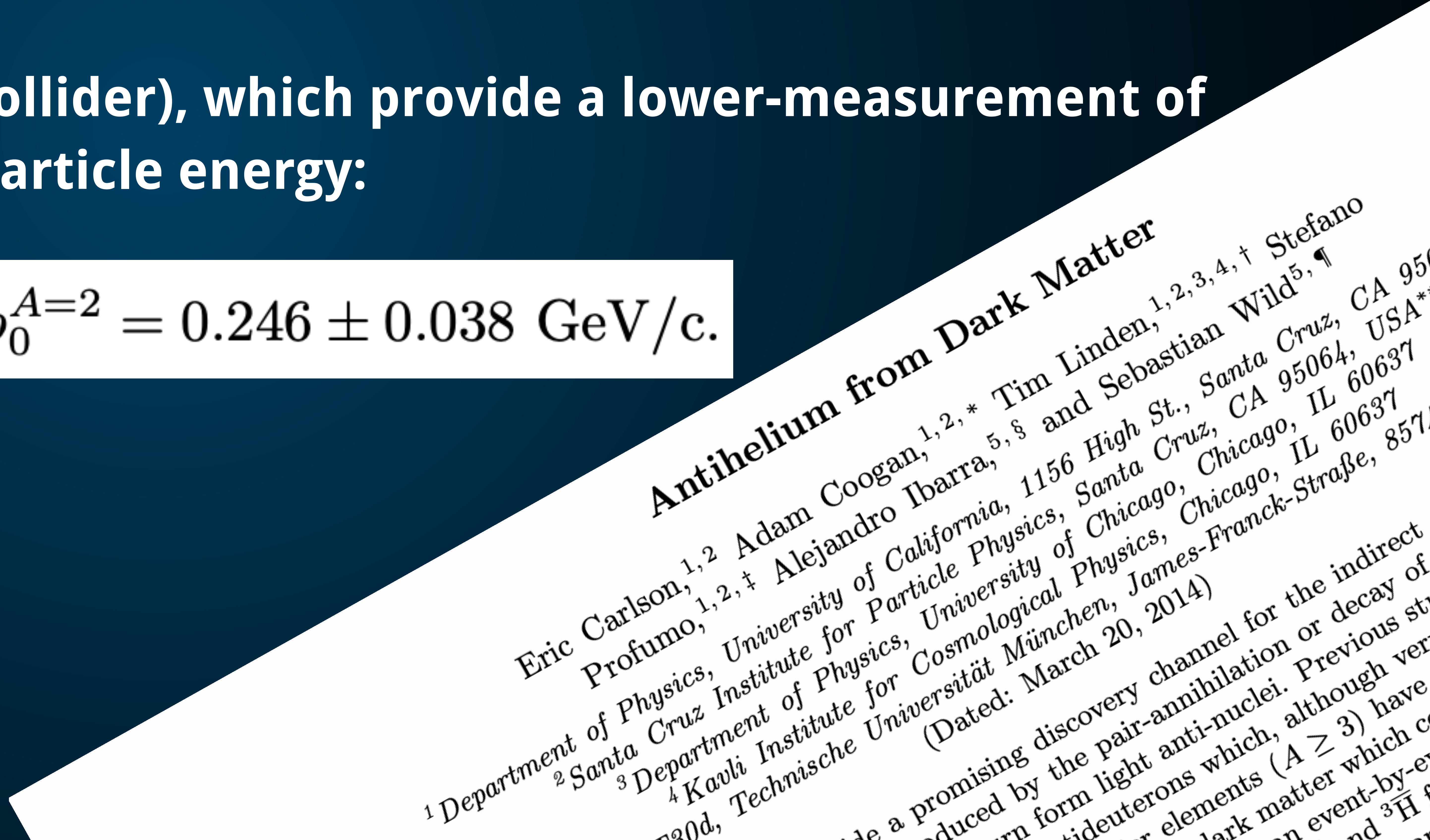
Key Insight - Coalescence Momentum for Antihelium Should Be Larger

While particle coalescence is hard to measure, the inverse process (fragmentation) is easier to measure. Helium's binding energy significantly exceeds deuteriums

$$p_0^{A=3} = \sqrt{B_{^3\overline{He}}/B_{\bar{D}}}\; p_0^{A=2} = 0.357 \pm 0.059 \text{ GeV/c}.$$

Can also use Heavy ion results (Berkeley Collider), which provide a lower-measurement of the coalescence momentum at a specific particle energy:

$$p_0^{A=3} = 1.28\; p_0^{A=2} = 0.246 \pm 0.038 \text{ GeV/c}.$$


Antihelium from Dark Matter

Eric Carlson,[1,2] Adam Coogan,[1,2,*] Tim Linden,[1,2,3,4,†] Stefano Profumo,[1,2,‡] Alejandro Ibarra,[5,§] and Sebastian Wild[5,¶]

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[2] Santa Cruz Institute for Particle Physics, Santa Cruz, CA 95064, USA
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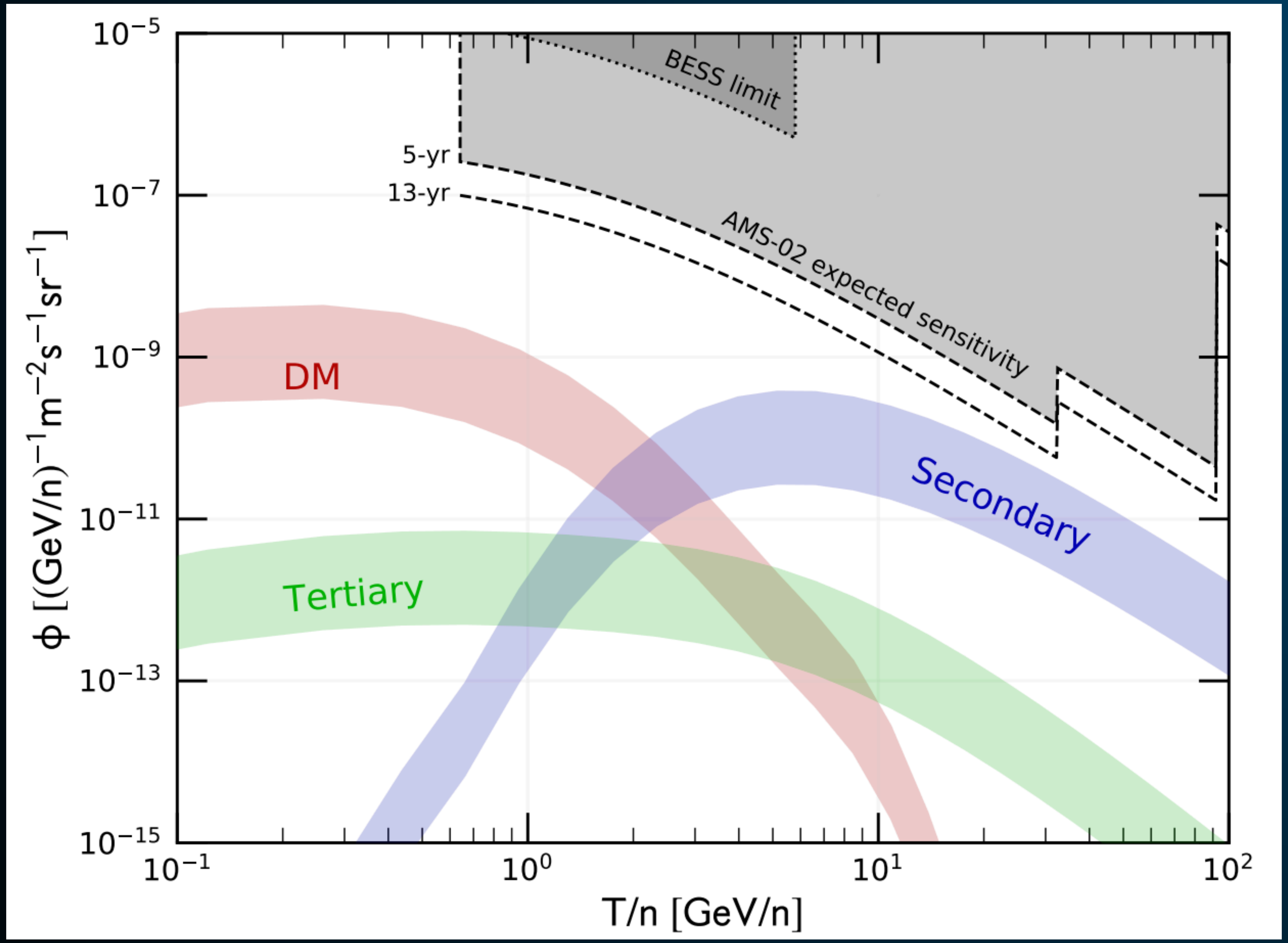
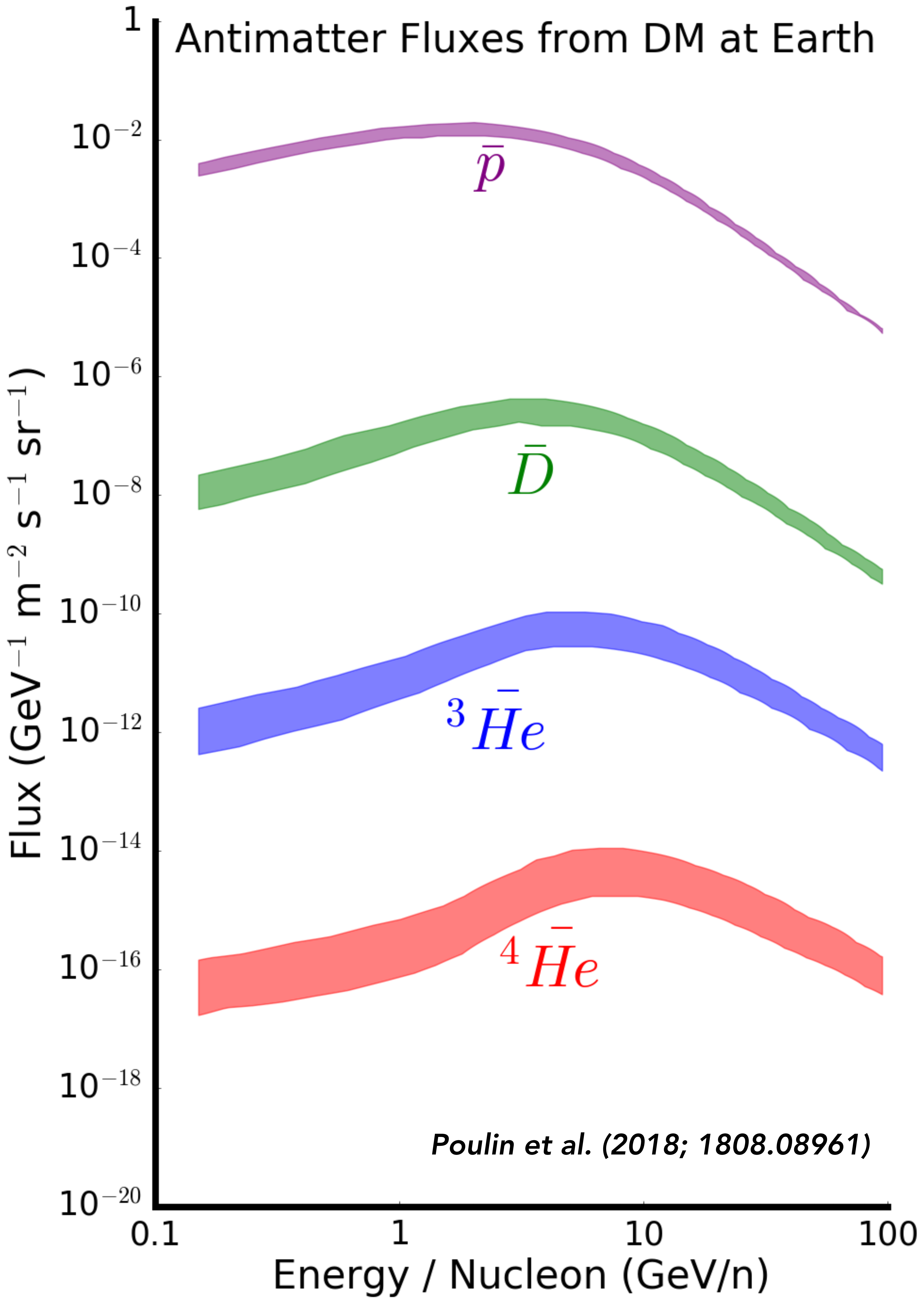
(Dated: March 20, 2014)

Coalescence Models - Expected Helium Flux

Using more realistic estimates for the anti helium coalescence momentum produces a boosted anti helium flux, especially at low energies.



Korsmeier (2017; 1711.08465)



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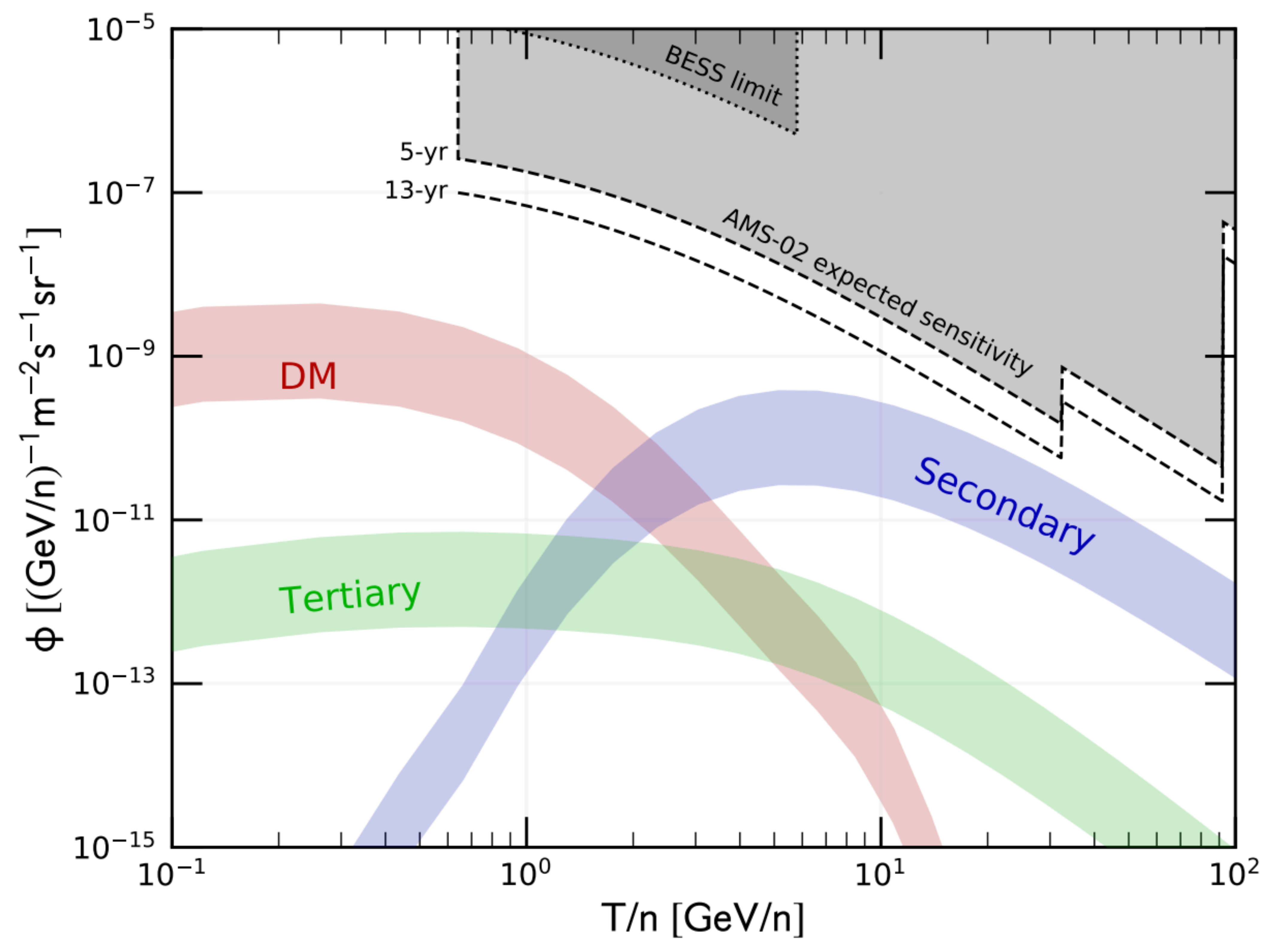
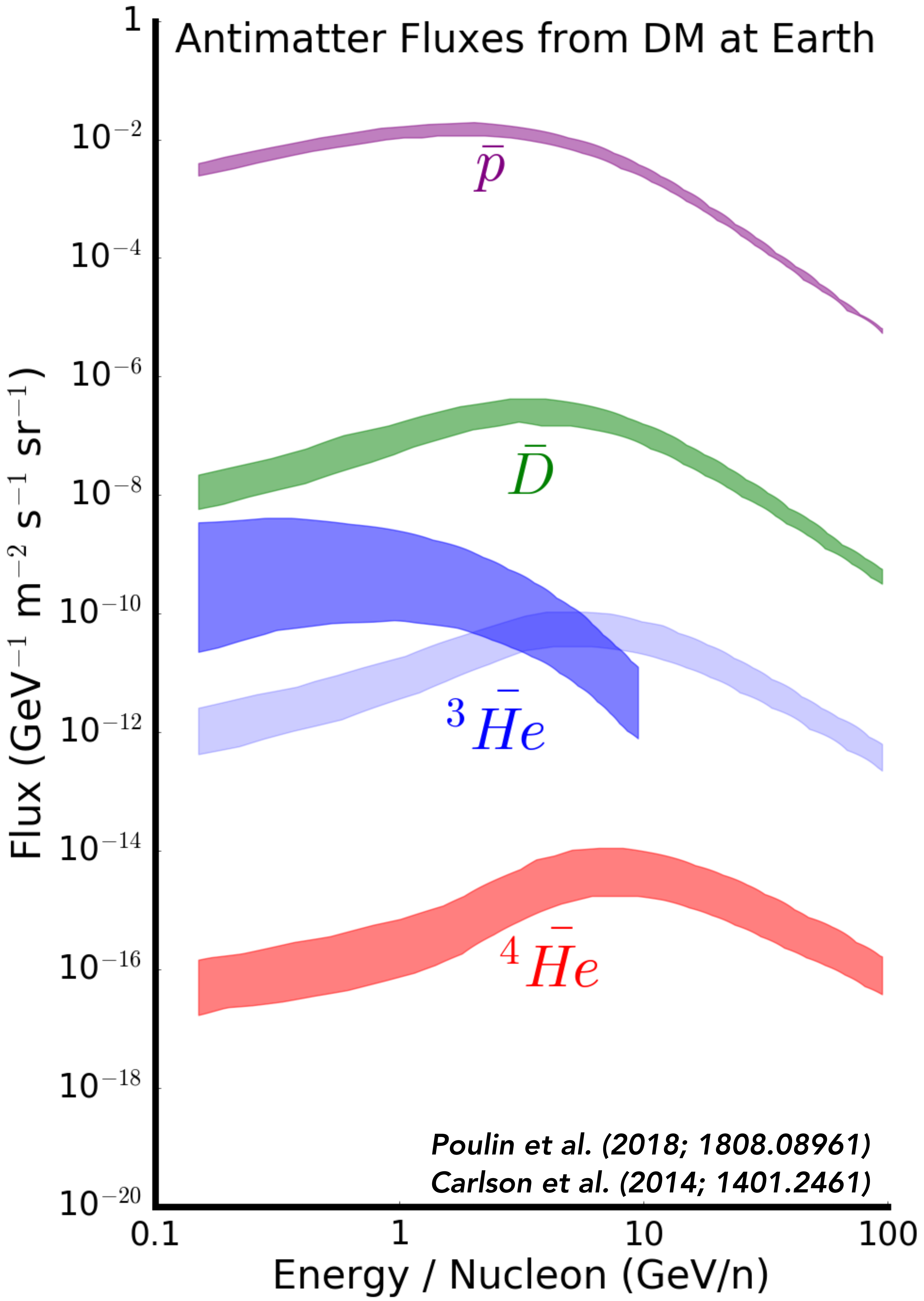
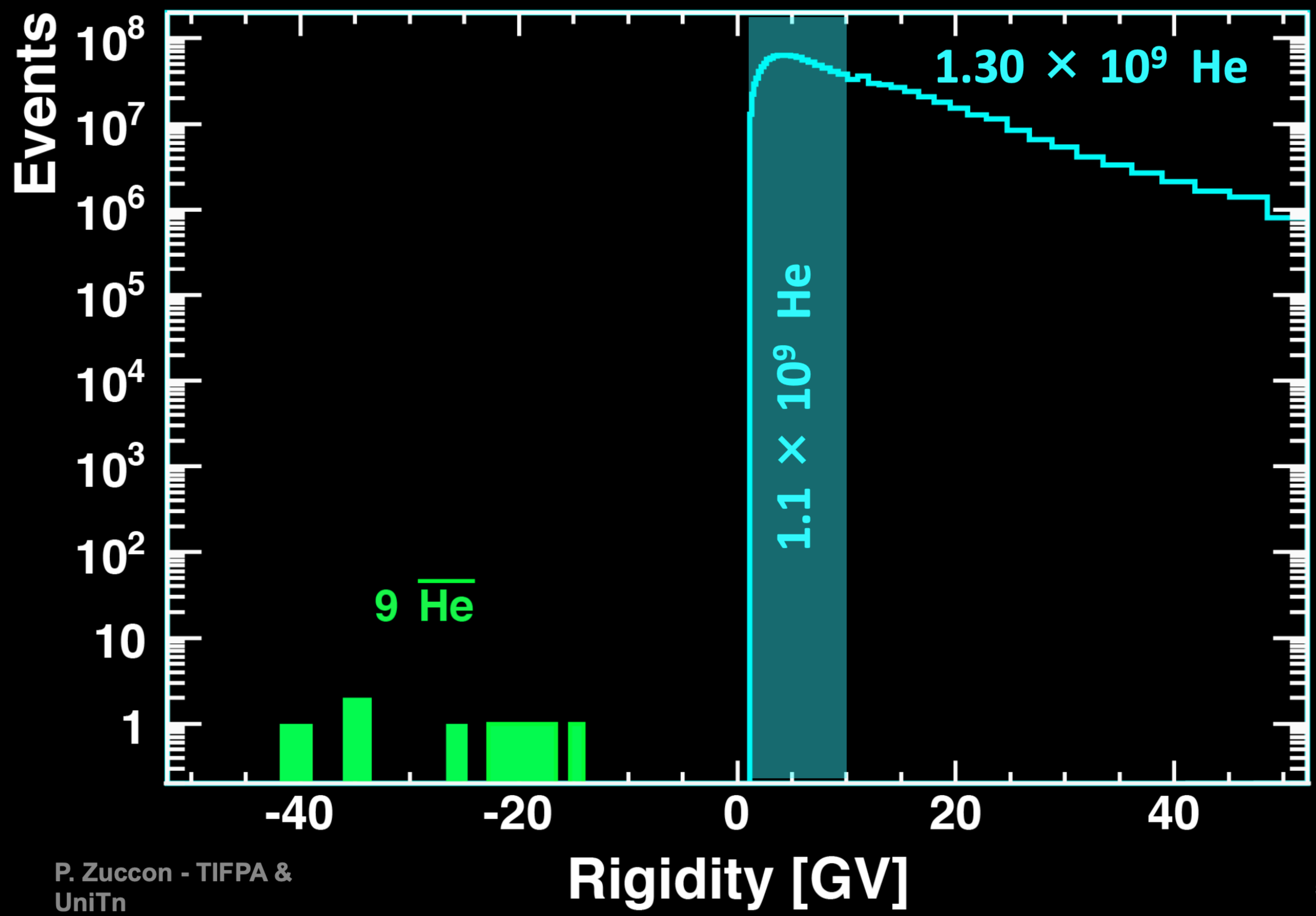


Korsmeier (2017; 1711.08465)



Poulin et al. (2018; 1808.08961)
Carlson et al. (2014; 1401.2461)

However the Rigidity of these Antihelium Events is High



Idea 2: A New Method for Producing Antihelium

Dark Matter Annihilation Can Produce a Detectable Antihelium Flux through $\bar{\Lambda}_b$ Decays

Martin Wolfgang Winkler[1, *] and Tim Linden[1, †]

[1]Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden

Recent observations by the Alpha Magnetic Spectrometer (AMS-02) have tentatively detected a handful of cosmic-ray antihelium events. Such events have long been considered as smoking-gun evidence for new physics, because astrophysical antihelium production is expected to be negligible. However, the dark-matter-induced antihelium flux is also expected to fall below current sensitivities, particularly in light of existing antiproton constraints. Here, we demonstrate that a previously neglected standard model process — the production of antihelium through the displaced-vertex decay of $\bar{\Lambda}_b$-baryons — can significantly boost the dark matter induced antihelium flux. This process can triple the standard prompt-production of antihelium, and more importantly, entirely dominate the production of the high-energy antihelium nuclei reported by AMS-02.

I. INTRODUCTION

The detection of massive cosmic-ray antinuclei has long been considered a holy grail in searches for WIMP dark matter [1, 2]. Primary cosmic-rays from astrophysical sources are matter-dominated, accelerated by nearby supernova, pulsars, and other extreme objects. The secondary cosmic-rays produced by the hadronic interactions of primary cosmic-rays can include an antinuclei component, but the flux is highly suppressed by baryon number conservation and kinematic constraints [3, 4]. Dark matter annihilation, on the other hand, occurs within the rest frame of the Milky Way and produces equal baryon and antibaryon fluxes [1, 5–7]

In this *letter*, we challenge the current understanding that standard dark matter annihilation models cannot produce a measurable antihelium flux. Our analysis examines a known, and potentially dominant, antinuclei production mode which has been neglected by previous literature – the production of antihelium through the off-vertex decays of the $\bar{\Lambda}_b$. Such bottom baryons are generically produced in dark matter annihilation channels involving b quarks. Their decays efficiently produce heavy antinuclei due to their antibaryon number and 5.6 GeV rest-mass, which effectively decays to multi-nucleon states with small relative momenta. Intriguingly, because any $^3\overline{\mathrm{He}}$ produced by $\bar{\Lambda}_b$ inherits its boost factor, these nuclei can obtain the large center-of-mass momenta necessary to fit AMS-02 data [13].

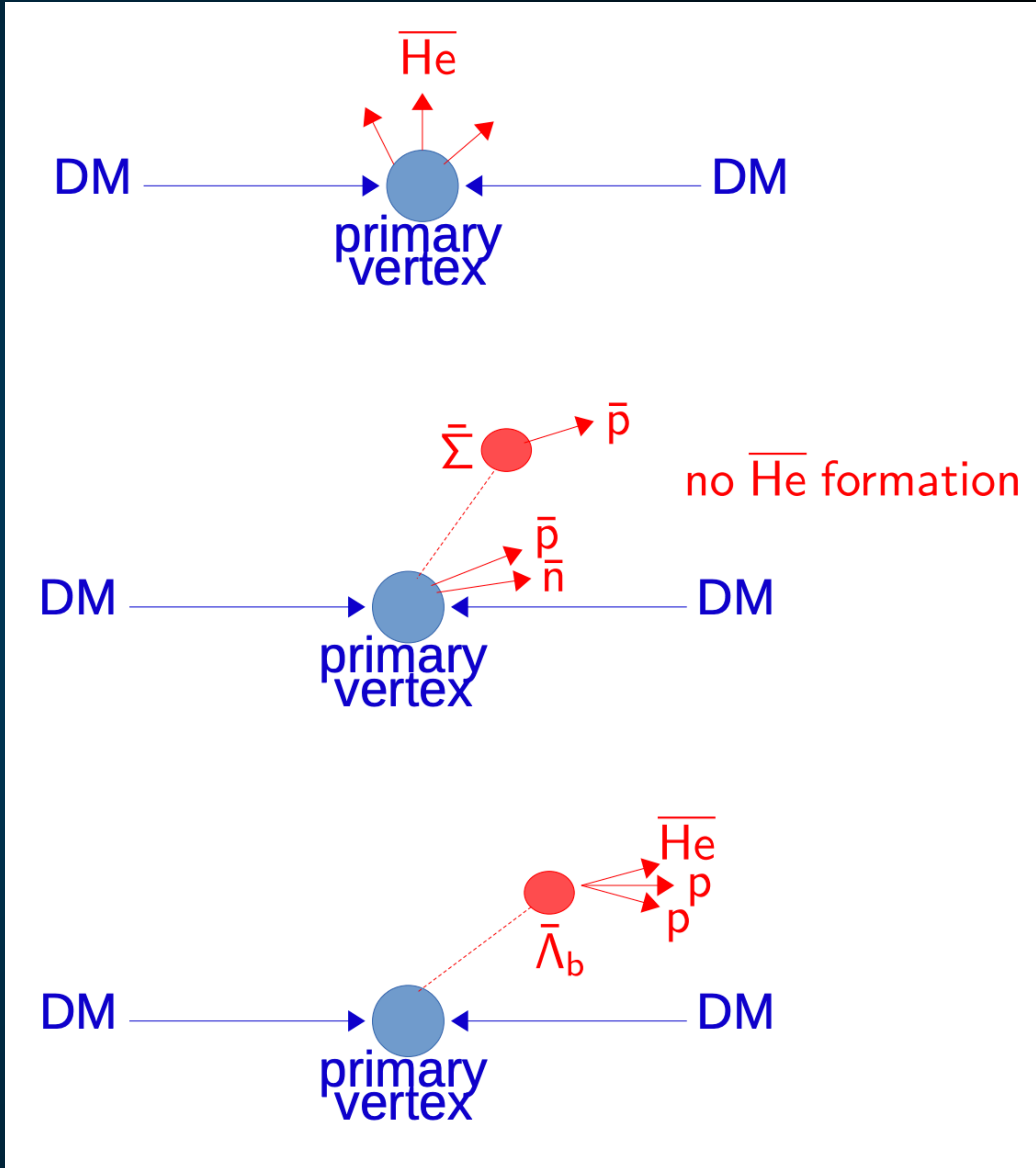
A Standard Model Resonance to Enhance Antihelium

Previous analyses have missed the (potentially) dominant contribution to anti-Helium production.

$\overline{\Lambda_b}$ **has correct parameters to produce** $^3\overline{He}$**:**

- **Antibaryon number of 1**
  - **Mass: 5.6 GeV** $(\bar{p}, \bar{p}, \bar{n}, p, p)$
  - **Or:** $\bar{p}, \bar{n}, \bar{n}, p, p$ **because** $^3H \rightarrow {}^3He$

$$R \propto p_0^{3(A-1)} \qquad R \propto \exp[-(\mathrm{p_i} - \mathrm{p_f})]$$

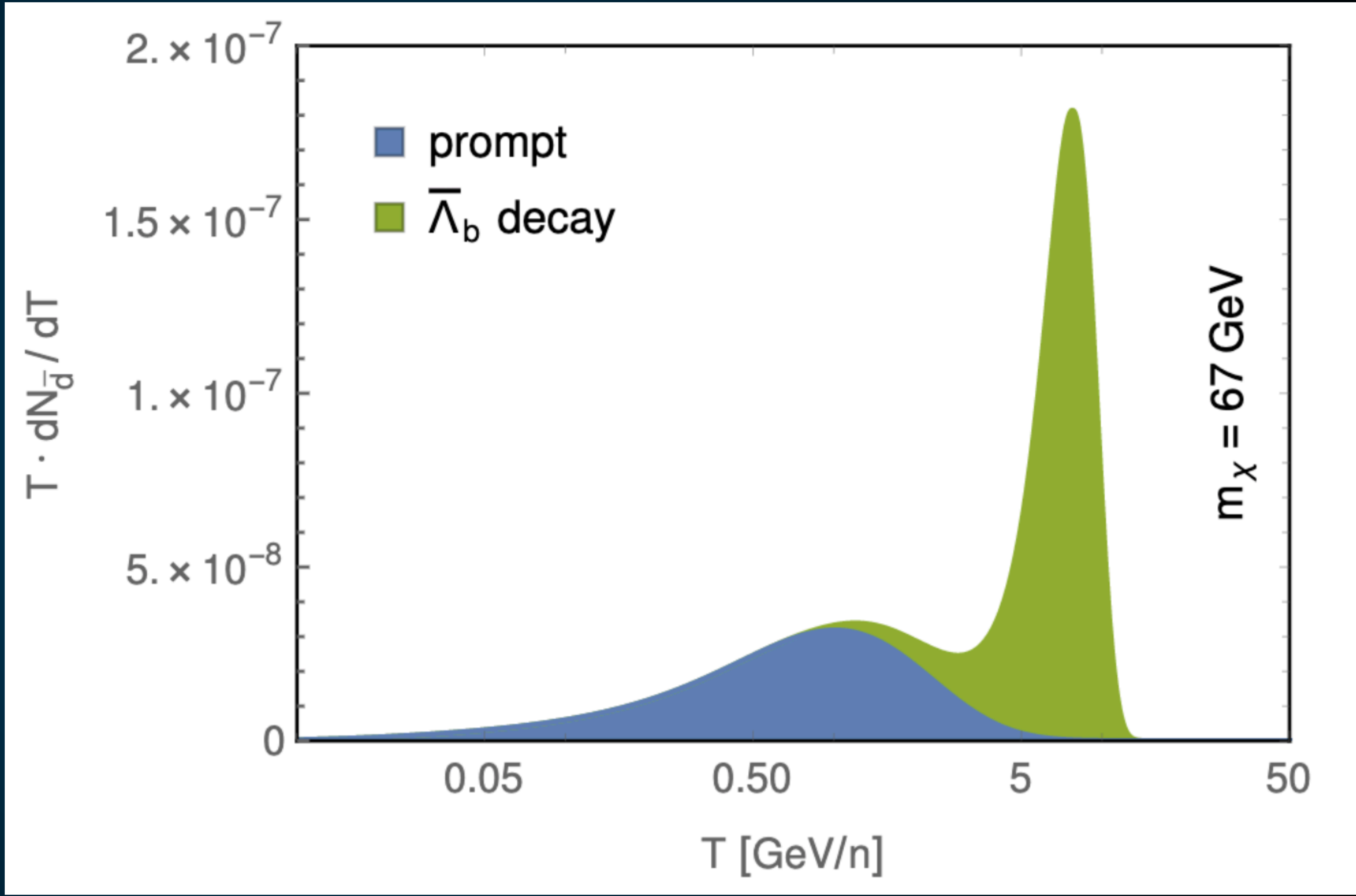


From: Martin Winkler

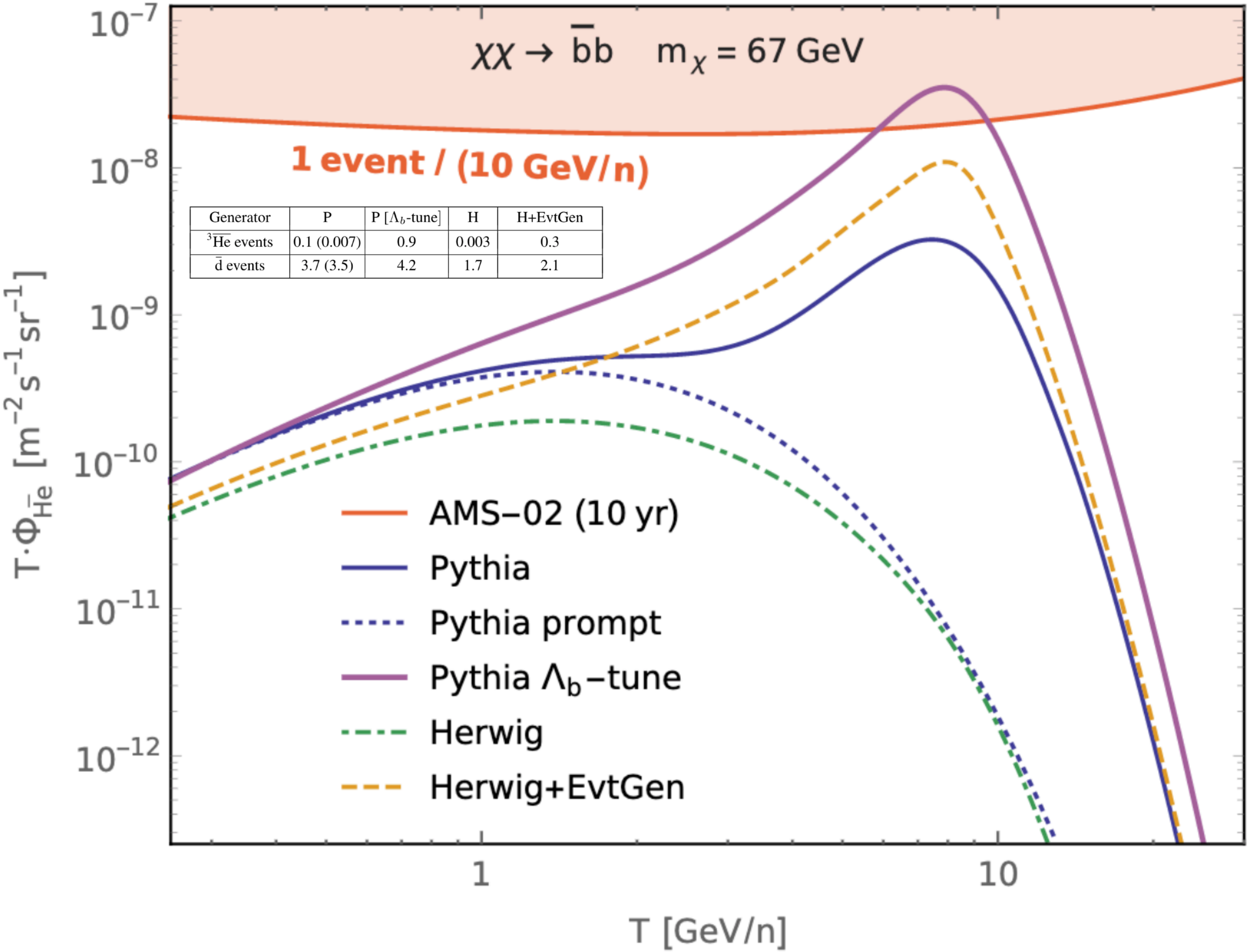
A High-Momentum Bump!

Can produce a significant enhancement of the total anti helium flux.

Moreover, the enhancement is at high-energies - matching the data.



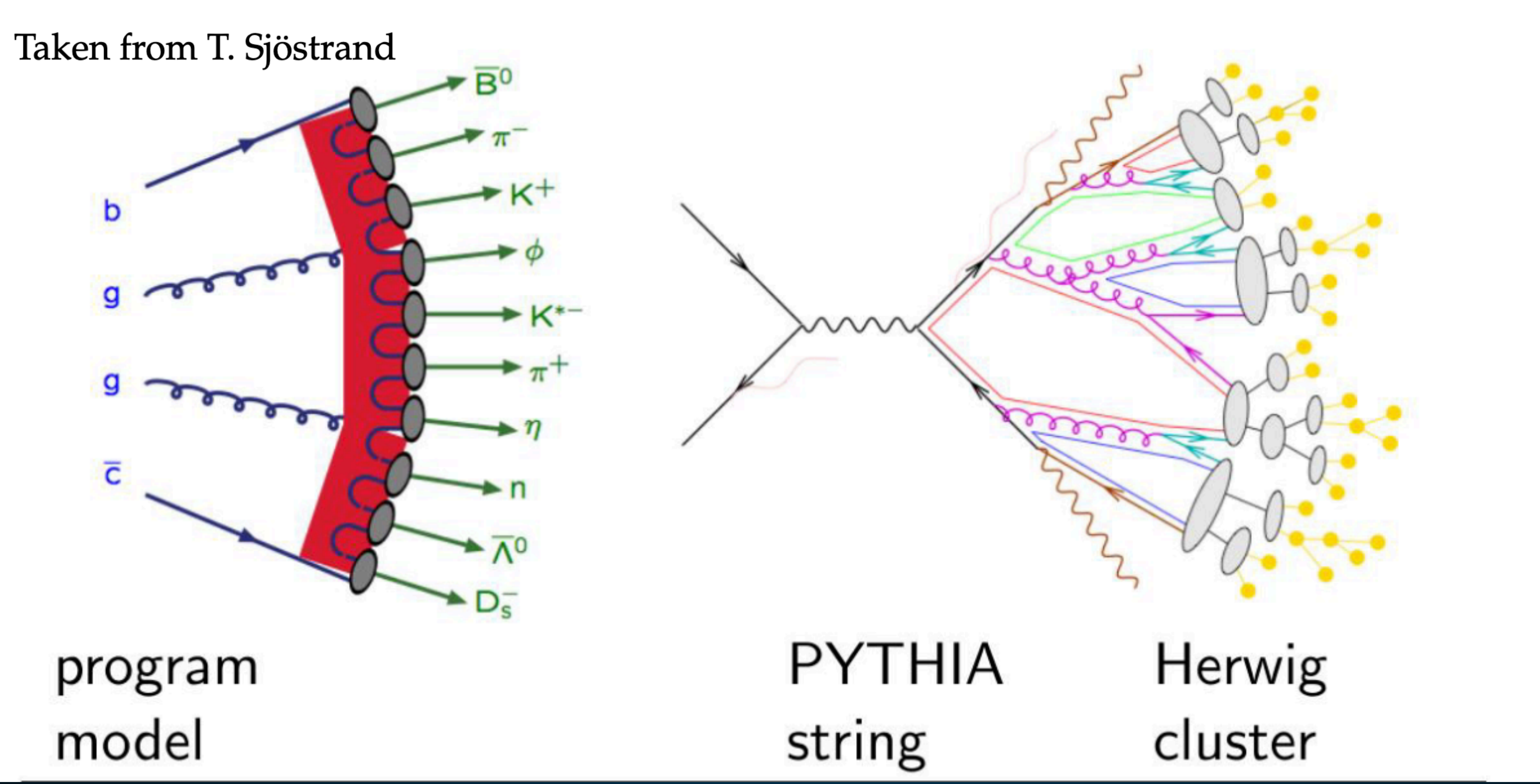
Winkler & Linden (2020; 2020.16251)



Generator	P	P [Λ_b-tune]	H	H+EvtGen
$^3\overline{He}$ events	0.1 (0.007)	0.9	0.003	0.3
$\bar{d}$ events	3.7 (3.5)	4.2	1.7	2.1

Uncertainties in the Rate

$\overline{\Lambda_b} \to {}^3\mathrm{He}$ rate



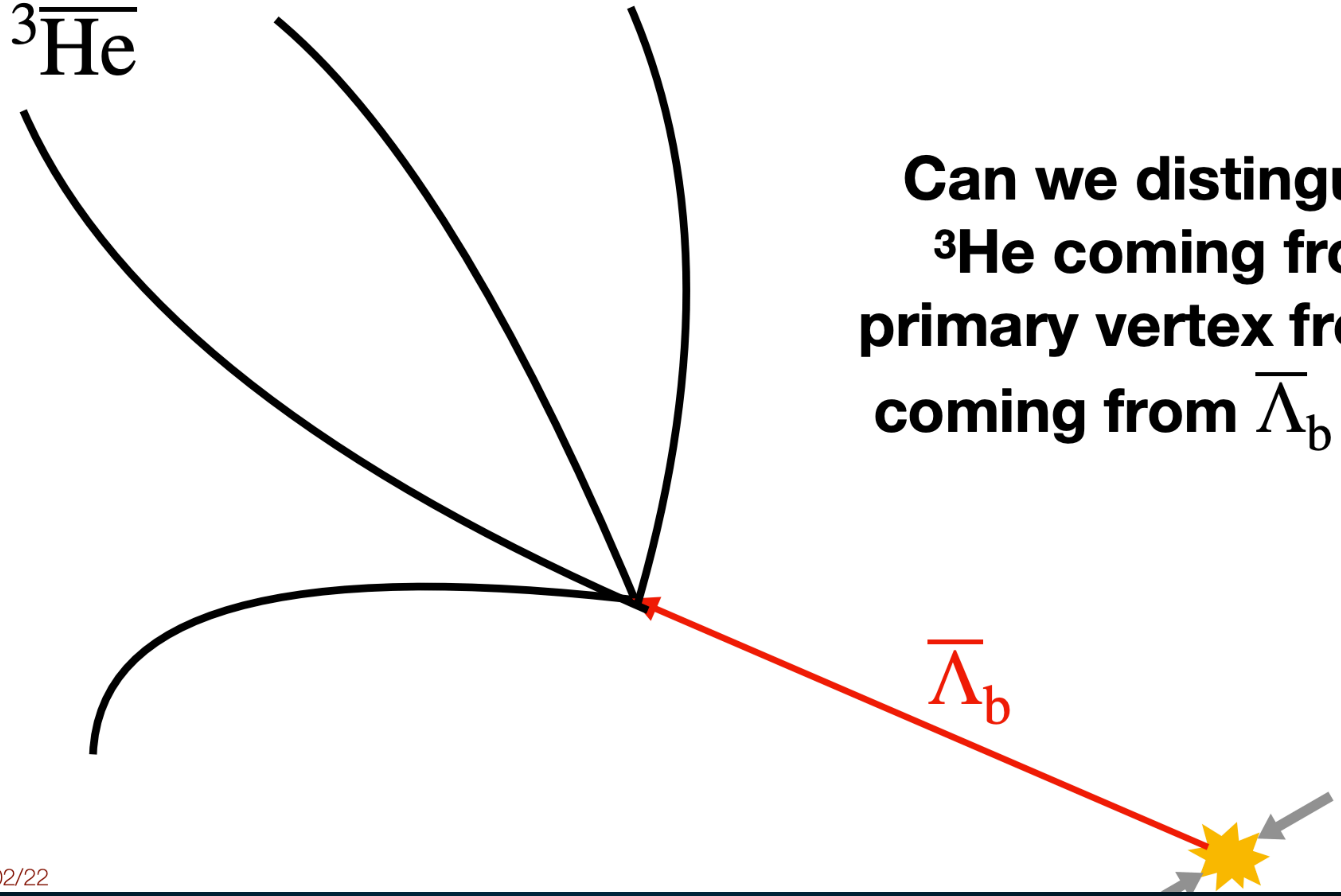
Pythia:

$$P(\overline{\Lambda_b} \to {}^3\overline{\mathrm{He}} + X) \sim 10^{-6}$$

Herwig:

$$P(\overline{\Lambda_b} \to {}^3\overline{\mathrm{He}} + X) \sim 10^{-9}$$

Can We Find this At Particle Accelerators?

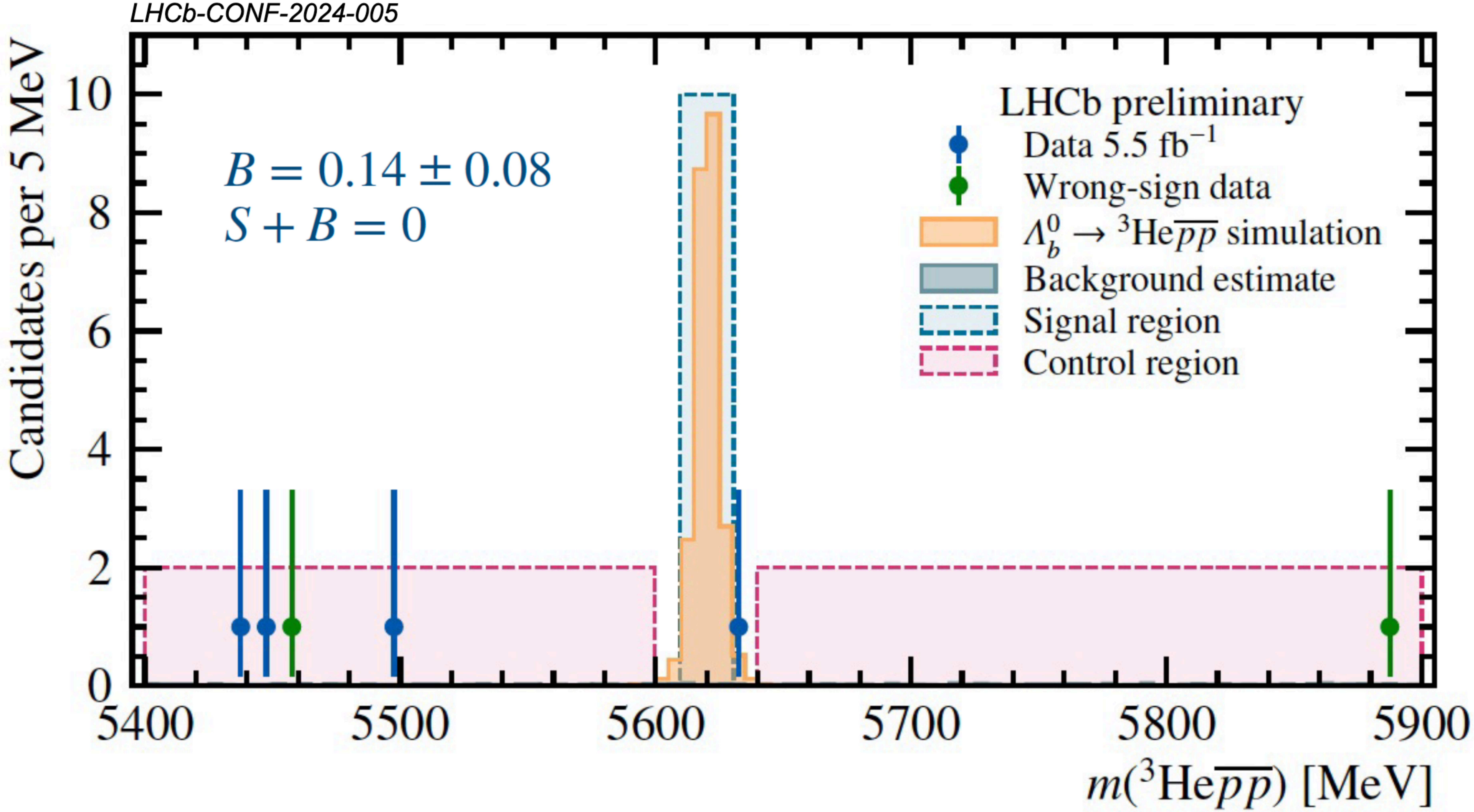


Can we distinguish the ^{3}He coming from the primary vertex from those coming from $\overline{\Lambda}_b$ decays?

$c\tau$ ~ 450 μm

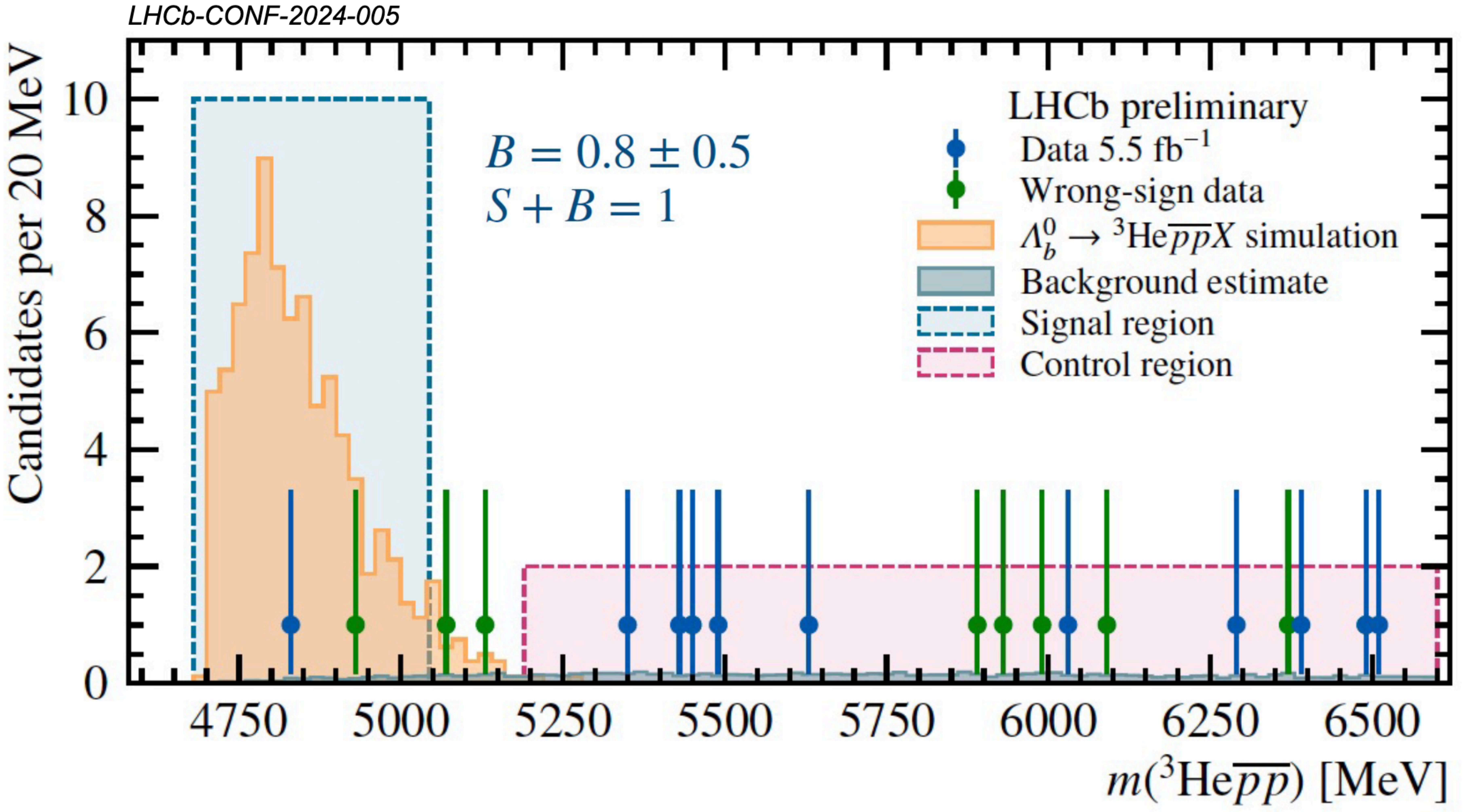
Search for antihelium from $\overline{\Lambda}_b^0$ decays: Invariant-mass spectra

$\overline{\Lambda}_b^0 \rightarrow {}^3\overline{\text{He}} + \text{p} + \text{p}$ (exclusive mode)



Search for antihelium from $\overline{\Lambda}_b^0$ decays: Invariant-mass spectra

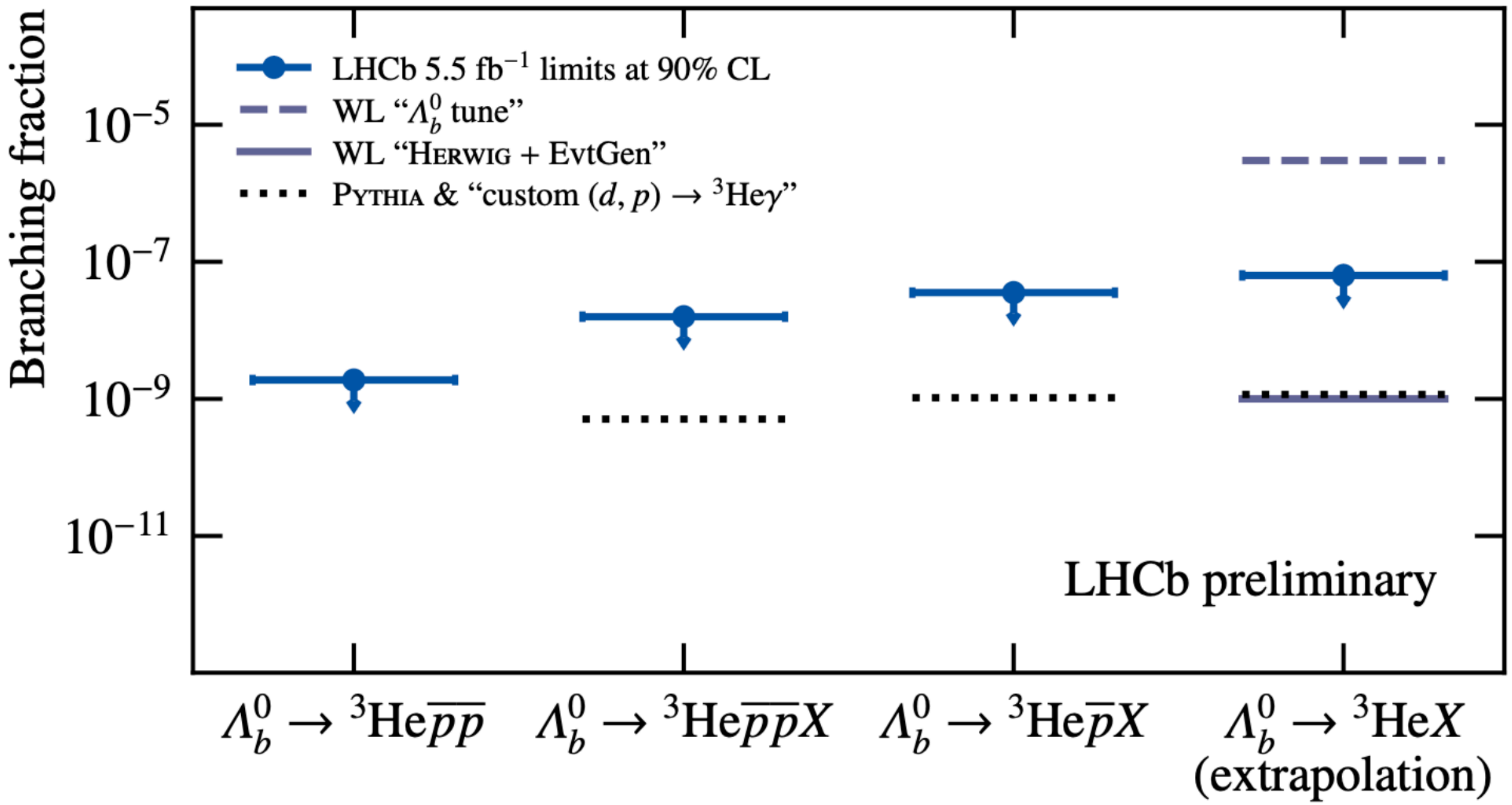
$\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}} + \mathrm{p} + \mathrm{p} + \mathrm{X}$ (inclusive mode)



Search for antihelium from $\overline{\Lambda}_b^0$ decays: Extrapolation to $\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}X)$

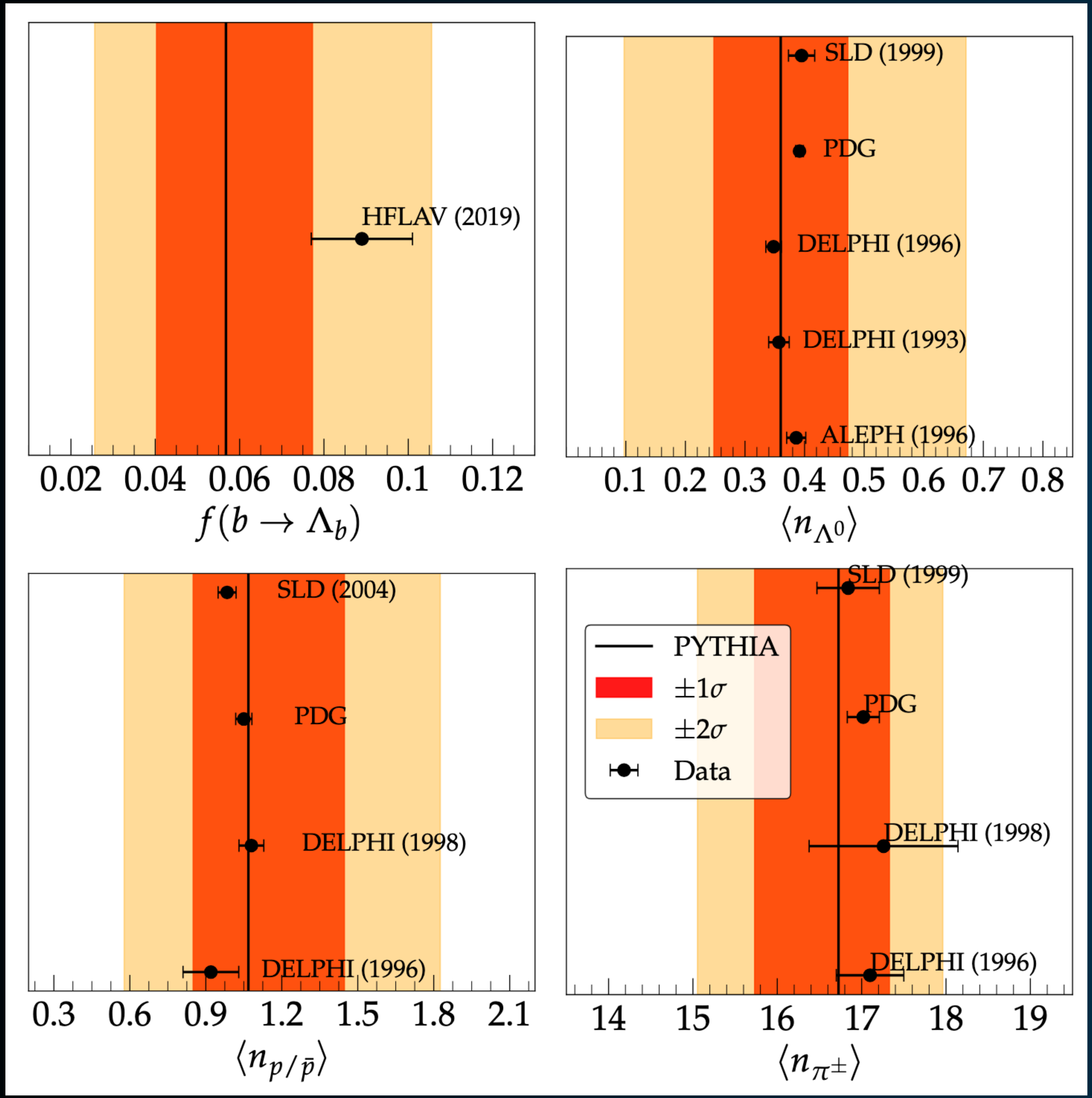
Conservative extrapolation assuming isospin symmetric production of nucleons

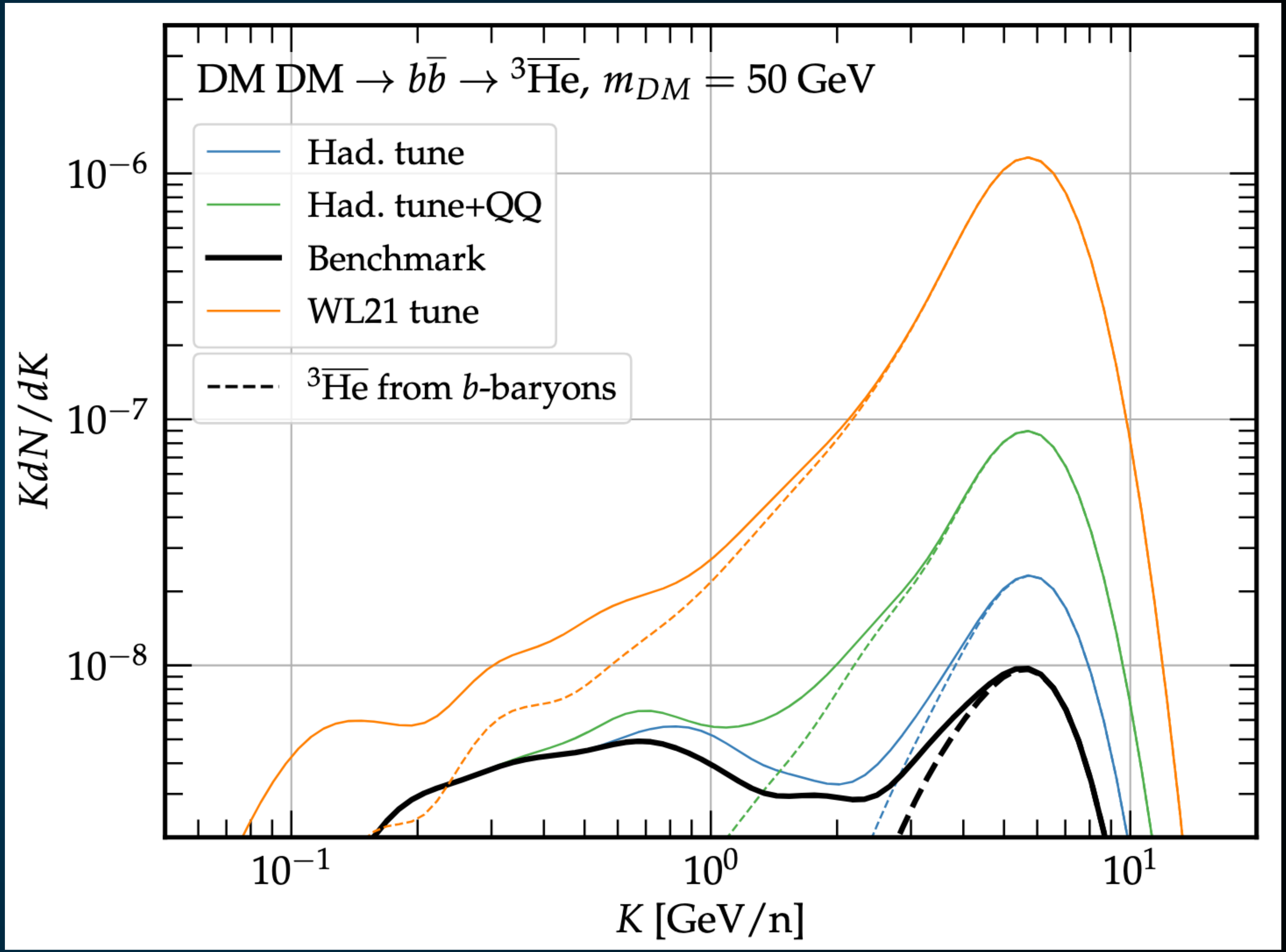
LHCb-CONF-2024-005



$$\mathcal{B}(\overline{\Lambda}_b^0 \to {}^3\overline{\mathrm{He}}X) < 6.3 \times 10^{-8} \text{ at } 90\% \text{ CL}$$

Uncertainties in the Rate





There are tunes of Pythia that decrease the expected anti-helium flux.

Di Mauro et al. (2504.07172)

Some Caveats

1.) LHCb results are preliminary

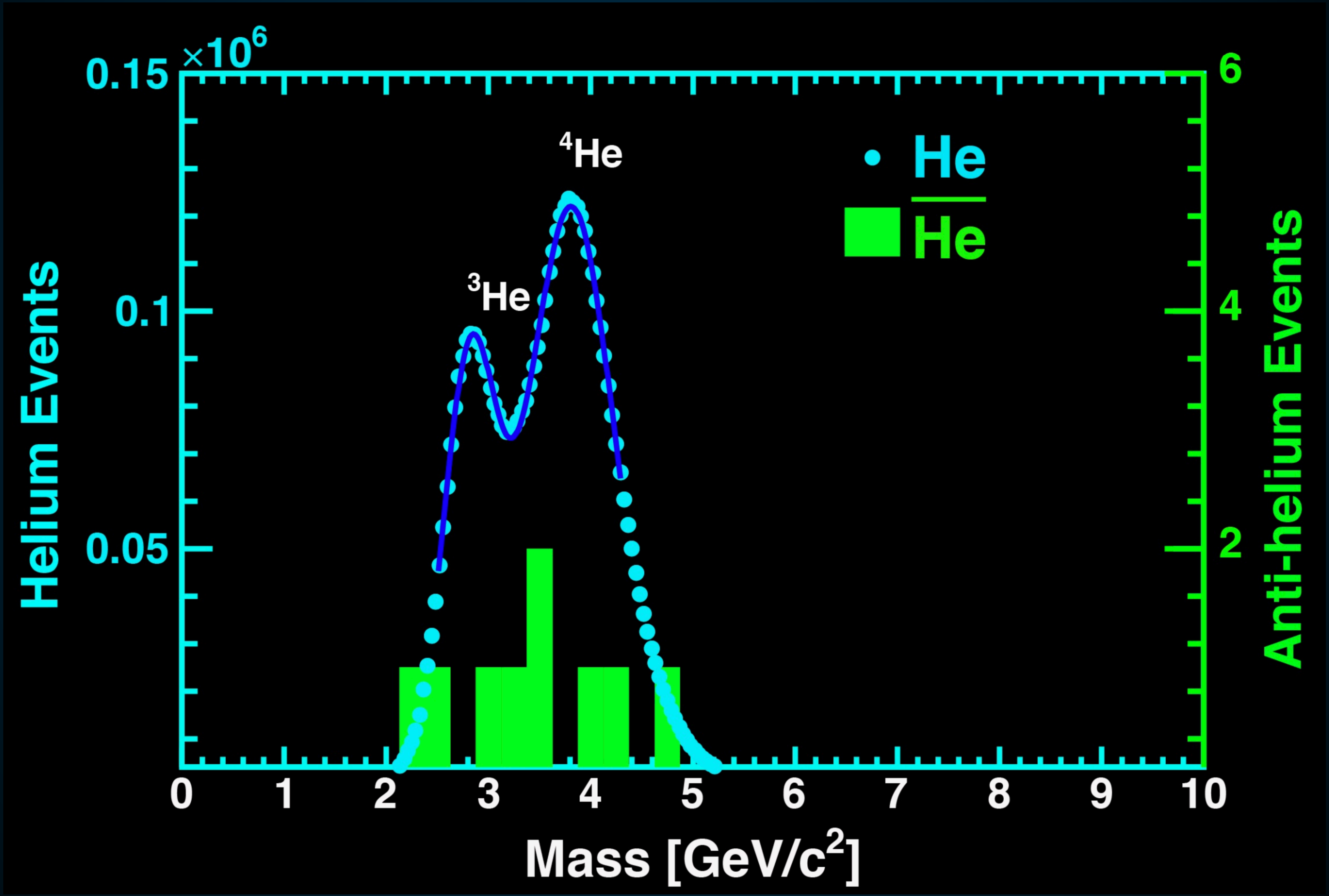
2.) There is a factor of two offset, because tritium decays to $^3\mathrm{He}$ in space.

- This can potentially be larger, because $\overline{p} + \overline{n} + \overline{n} + p + n$ has smaller kinetic energy (117 anti-tritium detected by LHCb, but no spectrum)

3.) Unclear how inclusive cross-sections are calculated with additional pions (which may make the momentum of the $\overline{^3\mathrm{He}}$ and p harder to distinguish).

4.) No searches for $\overline{^3\mathrm{H}} + n + n + \pi^+$. This could dominate, for example, if the proton and $\overline{^3\mathrm{He}}$ quickly re-annihilate due to Coulomb attraction.

Problem: Are We Actually Observing Antihelium 4?

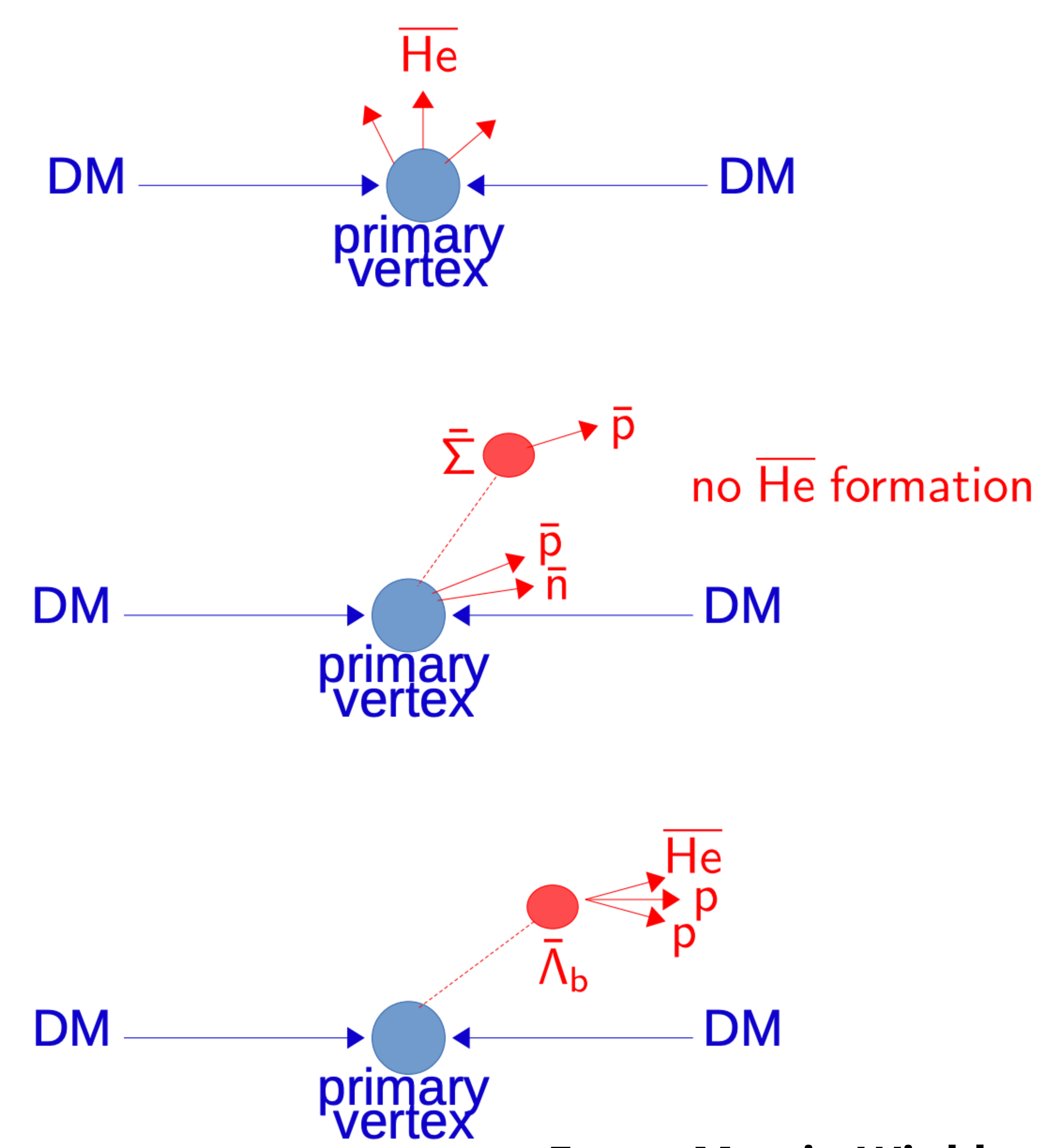


Cannot Enhance Antihelium-4 with Λ_b

$\overline{\Lambda}_b$ has correct parameters to produce $^3\overline{\mathrm{He}}$:

- Antibaryon number of 1
- Mass: 5.6 GeV

Too light to produce $^4\overline{\mathrm{He}}$!



From: Martin Winkler

Cosmic Ray Antihelium from a Strongly Coupled Dark Sector

Martin Wolfgang Winkler,[1,2,*] Pedro De La Torre Luque,[2,†] and Tim Linden[2,‡]

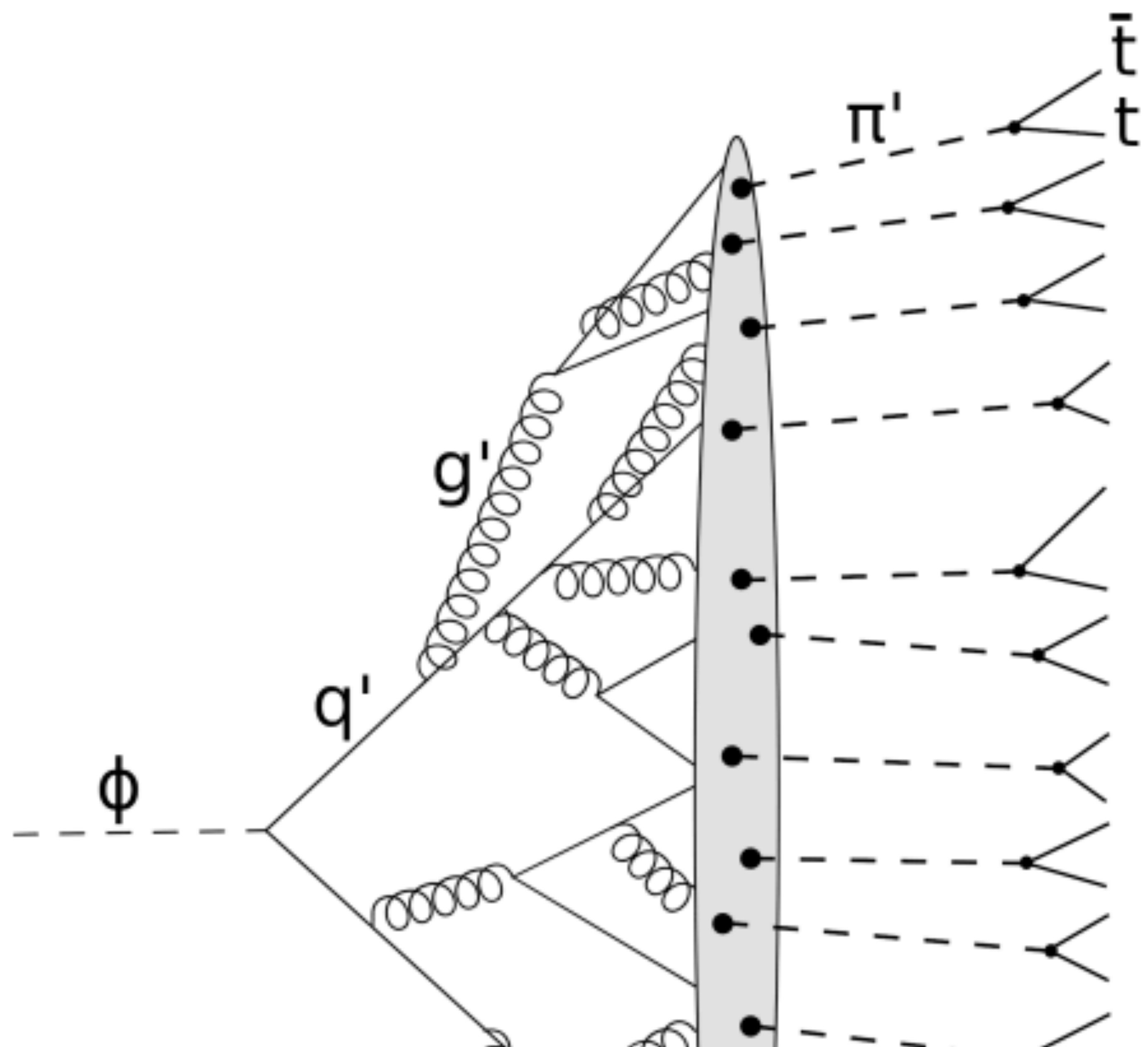
[1]*Department of Physics, The University of Texas at Austin, Austin, 78712 TX, USA*

[2]*The Oskar Klein Centre, Department of Physics, Stockholm University, AlbaNova, SE-10691 Stockholm, Sweden*

Standard Model extensions with a strongly coupled dark sector can induce high-multiplicity states of soft quarks. Such final states trigger extremely efficient antinucleus formation. We show that dark matter annihilation or decay into a strongly coupled sector can dramatically enhance the cosmic-ray antinuclei flux – by six orders of magnitude in the case of $^4\overline{\mathrm{He}}$. In this work, we argue that the tentative $^3\overline{\mathrm{He}}$ and $^4\overline{\mathrm{He}}$ events reported by the AMS-02 collaboration could be the first sign of a strongly coupled dark sector observed in nature.

I. INTRODUCTION

Cosmic-ray (CR) antinuclei are among the most promising targets in the indirect search for particle dark matter (DM). While the formation of antinuclei by DM annihilation or decay is strongly suppressed compared to *e.g.* gamma rays, the astrophysical antinuclei backgrounds – which arise from interactions of cosmic ray protons and helium with the interstellar gas – are extremely low. Therefore, the unambiguous discovery of even a single cosmic-ray antinucleus could provide smoking-gun evidence for particle DM [1, 2].



Strongly Coupled Dark Sectors

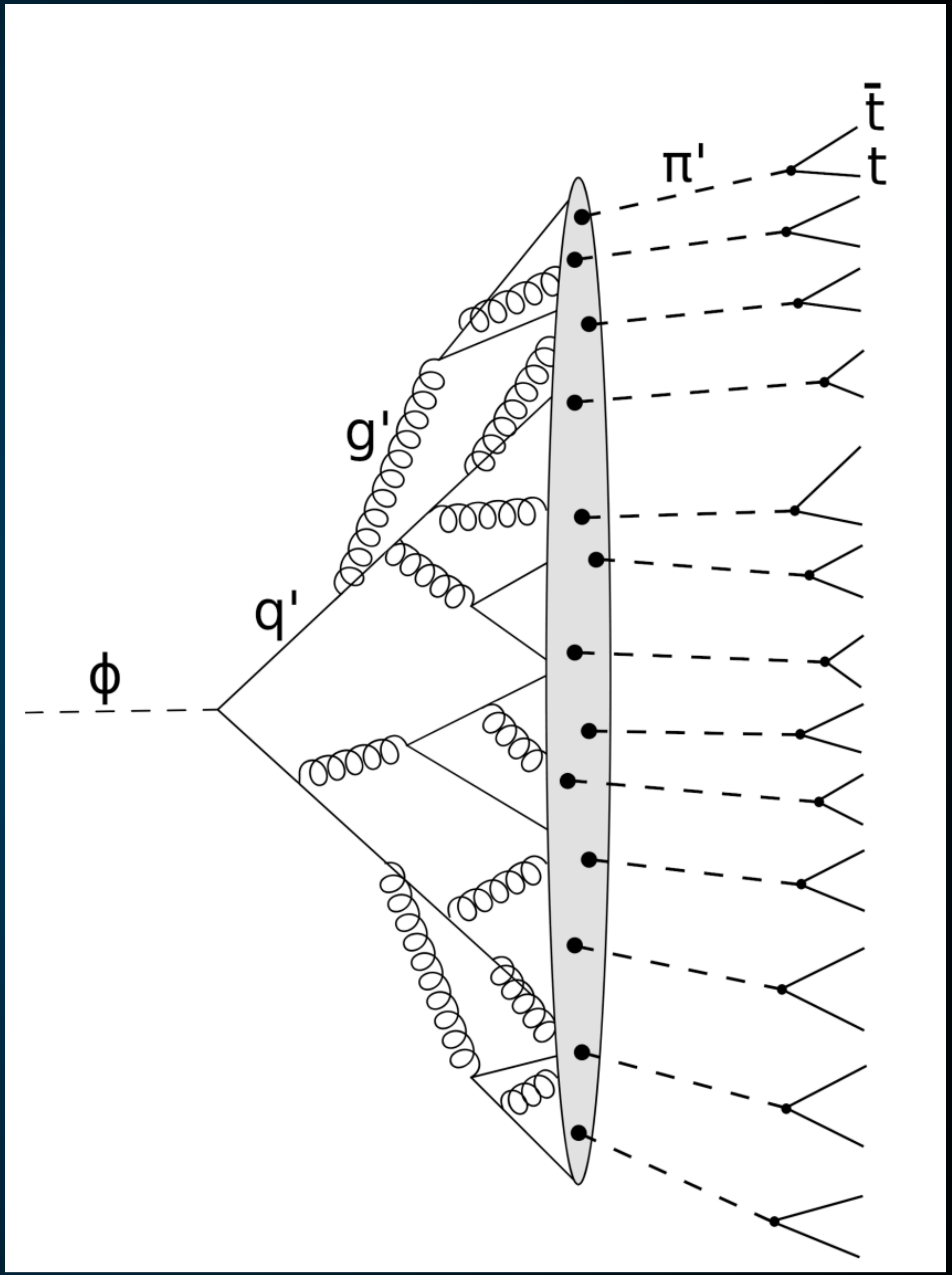
Just make a ton of quarks.

The production of heavy nuclei scales strongly with the number of quarks in the final state.

In QCD, a single 100 GeV annihilation produces O(100) pions

The dark matter model looks like a dark version of QCD.

$$\mathcal{L} \supset -\frac{1}{2}\,\mathrm{Tr}\,G'_{\mu\nu}G'^{\mu\nu} - \bar{q}'(i\not{D} - m_{q'})q'$$



Strongly Coupled Dark Sectors

The dark pions need to be very heavy — so the dark matter also has to be very heavy.

For annihilating dark matter — we are limited by unitarity.

For decaying dark matter, we are not.

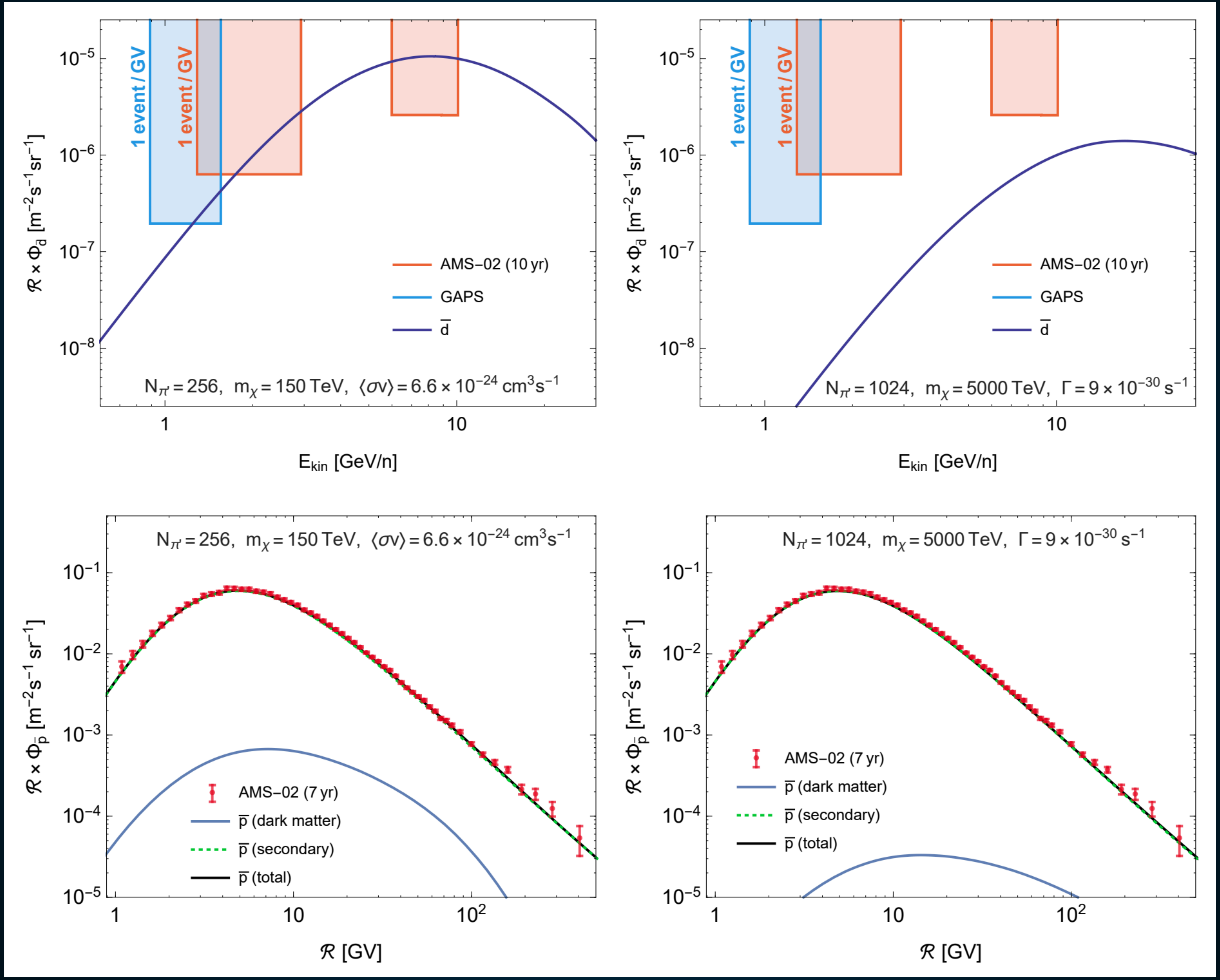
DM type	Annihilating	Decaying
Input Parameters		
m_χ [TeV]	150	5000
m_ϕ [TeV]	50.4	375
$m_{\pi'}$ [GeV]	380	700
$N_{\pi'}$	256	1024
$\langle \sigma v \rangle$ [cm^{3}s^{-1}]	6.6×10^{-24}	–
Γ [s^{-1}]	–	9×10^{-30}
Antinuclei Events at AMS-02		
$^3\overline{\mathrm{He}}$	15.6	20.3
$^4\overline{\mathrm{He}}$	1.0	3.1
$\bar{\mathrm{d}}$	19.3	1.2
Antinuclei Events at GAPS		
$\bar{\mathrm{d}}$	0.7	0

Strongly Coupled Dark Sectors

This significantly boosts the anti helium production rate:

By a factor of n^9 for $^3\overline{He}$ and n^{12} for $^4\overline{He}$

Strongly Coupled Dark Sectors



Conclusions

These are non-standard approaches. Even if dark matter is a WIMP, it may not produce antihelium.

However, if antihelium is detected, these are among the most reasonable methods for producing such an exotic particle.

All of these avenues are experimentally testable with upcoming colliders.